CONTRIBUTION OF ENVIRONMENTAL ISOTOPES TO THE UNDERSTANDING OF COMPLEX HYDROLOGIC SYSTEMS. A CASE STUDY: SIERRA DE GADOR, SE SPAIN

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ABSTRACT

Determining the content of ^{18}O and deuterium in the groundwater at the southern edge of the Sierra de Gador, between October 1991 and March 1993, has enabled identification of the flow system of the waters, the recharge and mixing processes and the possible mechanisms of salinization. Analysis of the precipitation indicates the dominant source and direction of the air masses. The local meteoric water line that is established indicates a primarily Mediterranean origin for the precipitation recharging the aquifers. The variation of ^{18}O content with altitude (–0·35 per mille per 100 m) enables an estimation of the principal recharge area, which corresponds to a zone between 1200 and 1800 m a.s.l. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

The isotopic content of groundwater has been used in diverse ways to resolve questions such as the age of the waters, the recharge area, origin of pollution and differentiation of flow systems (Zuber *et al*., 1995; Wood and Sanford, 1995). In many instances, this is more useful than other, non-isotopic techniques and, in any case, invariably provides a good complement to other methods. In our case, these techniques were applied to gain knowledge of the aquifers of Sierra de Gador, which have a complex geometry and function (Pulido-Bosch *et al*., 1991). The Sierra de Gador, a morphostructural domain characterized by abrupt orography, occupies an area of some 320 km^2 in southeastern Spain (Figure 1).

Over the last 30 years, the aquifers have been exploited intensively, notably altering the natural regime. Water-bearing formations on the southern side of the Sierra de Gador are hydrologically connected with the aquifer units of the Campo de Dalias, where more than 17 000 ha of highly profitable extra-early crops are currently irrigated, normally under plastic. Tourist activity has increased, especially in the eastern sector of the Campo where there are more than 100 000 visitors during the summer. In the early 1980s, the city of Almeria also began to use water from the Campo de Dalias, as other aquifers that had traditionally supplied it went dry. The mean volume pumped since then has been 1500 m^3 a^{-1}.

Marked irregularity of rainfall characterizes the climate in this region. The mean number of rainy days per year is 35. The rainfall gradient calculated in the area is 17 mm/100 m, with a consequent progressive decline in rainfall towards the east. The mean annual precipitation of the area for the period 1965/66 to 1990/91 was 289 mm but differences of up to 260 mm were recorded between areas of highest and lowest elevation in particular years. Precipitation takes the form of snow above 1800 m a.s.l on occasion. The mean annual temperature of the area (for the period 1965/66 to 1990/91) was 17·9°C, with daily minima as low as –6·6°C and maxima up to 36°C during the same year at the same station. In general, the area may be characterized as having a semiarid climate.

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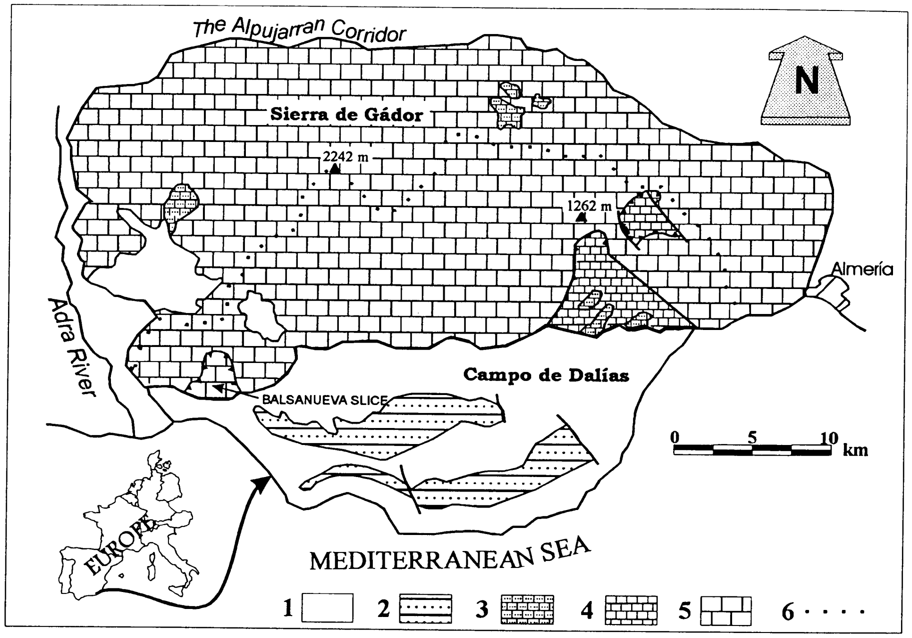

Figure 1. Location and hydrogeologic features of the study area: (q) Quaternary materials; (2) Pliocene calcarenites; (3) Miocene calcarenites; (4) Felix carbonates; (5) Gador carbonates; (6) watershed (simplified from Martín Rosales, 1996)

From a geological perspective, the outcropping rocks can be grouped into two broad categories: pre-orogenic and post-orogenic (Sanz de Galdeano, 1985). There are two pre-orogenic units: the Gador and the Felix (Figure 1). The Gador comprises a sequence of thick carbonates resting on metapelites. The Felix unit consists of a carbonate member with a thickness of less than 100 m that also overlies a metapelite member; it is overthrust on to the Gador. In both units, the lower metapelites are Permowerfenian in age and the carbonates are Triassic.

Post-orogenic rocks begin with Miocene calcarenites and limestones. Intercalated in the calcarenites are volcanic pebble conglomerates cemented by a volcanic matrix. Drilling data indicate that towards the interior of the Campo de Dalias (under a Plio-Quaternary covering), these strata grade into marls with gypsums and conglomerates (Rodríguez Fernández and Martin Penela, 1993). Pliocene deposits locally attain more than 500 m in thickness, beginning with a thin basal conglomerate which supports a succession of blue marls containing increasing amounts of sand upwards. The sandy marls gradually change to calcarenites of up to 150 m in thickness. The Quaternary materials display greatly varied facies, the most abundant being alluvial fans (Goy and Zazo, 1986) which border the foothills of the Sierra de Gador and reach 150 m in thickness. In addition, there are red silts in the central Campo and several generations of glacis and older beach sediments, plus modern dunes and beach deposits towards the coast.

From a tectonic point of view (Sanz de Galdeano, 1985), two aspects are noteworthy: the presence of overthrusting and of intense fracturing. As noted, there is overthrusting of the Felix unit upon the Gador. Tectonic fracturing has continued during the Quaternary (Fourniquet, 1977), clearly controlling the sedimentation (Rodríguez Fernández and Sanz de Galdeano, 1992).

HYDROLOGICAL FRAMEWORK

The carbonates of the Gador and Felix units are highly permeable but contain intercalated calcoschists of low permeability. The Miocene and Pliocene calcarenites, the conglomerates, marine terraces and the gravels that constitute the Quaternary alluvial fans are also permeable. The transmissivity values of the carbonates can reach more than 10 000 m^2 day^{-1}, with high porosity. In the Miocene deposits, the transmissivity varies between 200 and 6000 m^2 day^{-1} (IGME, 1982). The dolomitic limestones of the Gador and Felix units are hydraulically connected with the Balanegra and Aguadulce aquifer units in Campo de Dalias. A third aquifer in Campo de

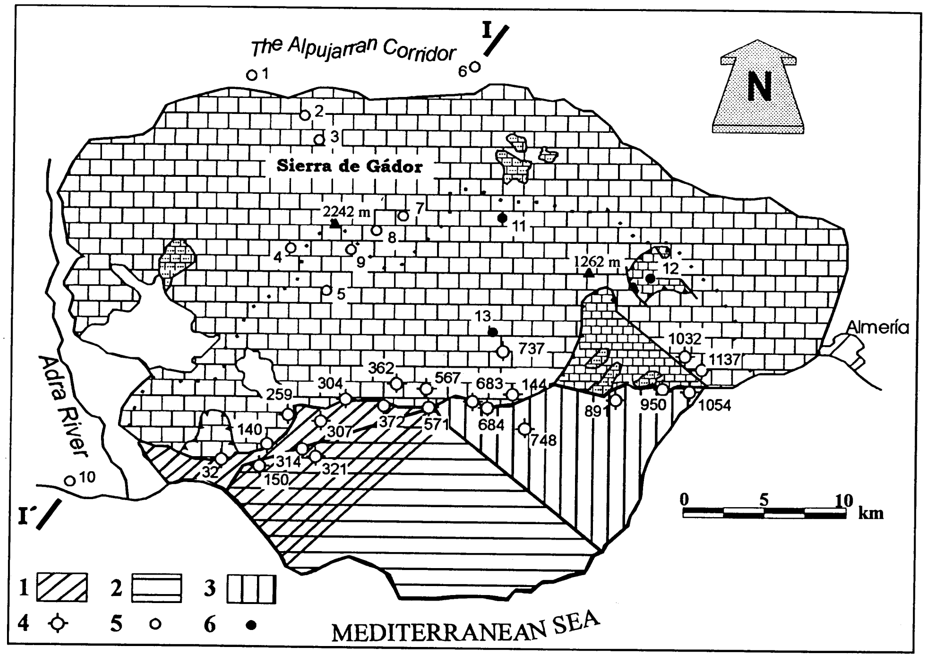

Figure 2. Hydrogeologic units differentiated in the Campo de Dalias and location of the sampling wells: (1) Balanegra; (2) Balerma-Las Marinas; (3) Aguadulce; (4) sampling wells; (5) sampling station for precipitation (data from Araguás, 1991); (6) sampling station for precipitation. The hatched area corresponds to two overlapping aquifers that are separated by an impermeable layer. (I–I', cross-section shown in Figure 3)

Dalias, Balerma-Las Marinas, is formed in underlying Pliocene calcarenites; it is hydraulically separated from the other Campo aquifers by impermeable strata (Figure 2).

The schists, phyllites and quartzites of both alpujarride mountain units are almost impervious, as are the deepest Miocene facies and the Pliocene marine marls. The volcanic pebble conglomerates and the volcanic rocks themselves are sparingly permeable.

In addition to the natural outflow, the quantity of water being pumped from the system is $126\times10^6\,m^3\,a^{-1}$ (1993/94), while recharge equals $50\times10^6\,m^3$ (Domínguez and González, 1995). This imbalance between input and output of water is causing a decline in the piezometric level, which has led to salt-water intrusion in the Aguadulce unit. The recharge differs greatly between units and has now been forced to change from an unaffected regime to the present one. In a natural regime, the principal input comes from the direct infiltration of rainfall, especially in the Sierra de Gador. The natural flow appears to be predominantly in a north-to-south direction, and is continued into the Balerma-Las Marinas unit, resulting in the discharge of this unit in bordering wetlands towards the coast. In the Balanegra and Aguadulce units, the natural flow was essentially west-to-east because the most important spring (Aguadulce, meaning 'freshwater') was situated on the coast.

With the increased exploitation of the groundwater system, the different aquifer units became disconnected as the piezometric level fell to and below the position of the underlying impervious materials. In this new situation, the Aguadulce unit began to be invaded by seawater along upconings that appeared, and at the same time must have discharged less freshwater into the sea. This phenomenon is not detected in the Balanegra unit because the sea–aquifer contact is restricted to a small sector called the Balsanueva Slice.

The southern side of the Sierra de Gador ($320\,km^2$ in area) is seriously vulnerable to flash floods. The abrupt relief, the steep slopes (exceeding 40 per cent), the drainage network with great erosive power and sediment load capacity, together with the erratic distribution and intensity of the rainfall, are circumstances favouring torrential behaviour in the gullies dissecting the mountains. Erosion has been worsened by intense deforestation during the last two centuries. To reduce the flood risks and facilitate infiltration into the limestones and dolomites, a total of 107 small retention dams have been constructed on the south slope. The capacity height of

Table I. Results of the isotopic analyses (in ‰) of groundwater samples

Date	140 ^{18}O	140 D	372 ^{18}O	372 D	567 ^{18}O	567 D	737 ^{18}O	737 D	1137 ^{18}O	1137 D
Oct. 91	–8·18	–52·4	–8·14	–50·0	–7·97	–50·5	–8·93	–56·5	–8·52	–54·5
Nov. 91	–8·17	–52·6	–8·36	–52·0	–8·23	–51·9	–8·78	–56·8	–8·35	–54·0
Dec. 91	–7·96	–55·8	–8·13	–54·8	–7·77	–54·2	–8·85	–58·5	–8·23	–52·6
Jan. 92	–8·11	–52·0	–8·36	–52·8	–8·14	–50·5	–8·63	–55·6	–8·30	–53·7
Feb. 92	–8·09	–54·4	–8·37	–53·1	–8·32	–50·9	–8·74	–56·4	–8·40	–56·1
Mar. 92	–8·07	–47·9	–8·39	–52·9	–8·32	–52·2	–8·68	–58·3	–8·45	–55·3
Apr. 92	–8·03	–50·4	–8·69	–53·3	–8·27	–51·6	–9·03	–56·6	–8·96	–54·3
May 92	–8·23	–53·6	–8·06	–51·8	–7·92	–53·5	–8·73	–55·0	–8·31	–56·0
Jun. 92	–8·03	–53·0	–	–	–8·11	–50·4	–8·80	–56·4	–8·56	–52·8
Jul. 92	–8·00	–53·5	–8·00	–51·2	–8·00	–50·0	–8·30	–56·1	–8·20	–53·4
Aug. 92	–8·00	–52·4	–8·00	–51·9	–8·00	–51·8	–8·40	–54·5	–8·30	–53·0
Sep. 92	–8·10	–51·0	–8·10	–52·2	–8·00	–52·4	–8·60	–52·2	–8·20	–53·0
Oct. 92	–8·10	–50·3	–	–	–7·90	–52·2	–8·60	–56·8	–8·30	–56·6
Nov. 92	–8·00	–51·9	–8·20	–49·8	–7·90	–54·3	–8·50	–55·8	–8·50	–52·3
Dec. 92	–7·80	–52·8	–8·00	–49·4	–8·00	–53·7	–8·40	–55·4	–8·30	–53·2
Jan. 93	–8·30	–49·8	–8·20	–52·0	–8·00	–51·8	–8·60	–54·2	–8·50	–52·5
Feb. 93	–8·00	–51·4	–8·30	–50·5	–8·00	–49·5	–8·80	–54·4	–8·20	–53·3
Mar. 93	–	–	–8·30	–51·2	–	–	–8·80	–55·1	–8·30	–53·5

the dams examined varied from 3 to 14 m, with lengths up to 45 m (Pulido-Bosch *et al*., 1994). It is proposed to add a significant number of new dams.

From a hydrogeological perspective, the dams increase infiltration of runoff water that is retained, which contributes to the recharge of the carbonate aquifer of the Sierra. This explains the need to identify the most permeable sectors in order to best position the dams for protection and correction of the gullybed and thereby harness the torrential runoff. Study of stable isotope patterns in the water enables the location of the principal recharge areas to be determined and provides more thorough knowledge of the functioning of the aquifer. This, coupled with the geological information, will facilitate the task of deciding where to place the new infiltration dams.

RESULTS FROM THE STABLE ISOTOPE ANALYSIS

The isotopic determinations were carried out in the Stable Isotope Geochemical Laboratory of the Experimental Station of the Zaidin (CSIC, Granada, Spain), and in the Laboratory of Environmental Studies of the Hungarian Academy of Sciences (Debrecen), following the classic methods of Epstein and Mayeda (1953). The waters to be used for determination of isotopic composition were placed inside sample containers with a quantity of pure CO_2, and maintained at 25·5°C for 12 h. Under these conditions, isotopic equilibrium develops between the H_2O and the CO_2. The separated CO_2 was then transferred to a mass spectrometer where the isotopic composition was determined. The analytical precision was ±0·05 per mille for ^{18}O and ±1 per mille for ^{2}H. All data are expressed in amounts per mille, and the reference standard used was V-SMOW.

Study of the isotopic composition is based on data from monthly samples taken between October 1991 and March 1993 in five wells located at the foot of the Sierra de Gador (Table I). A more extensive spatial network was established and sampled on two occasions (June and September 1993) for ^{18}O (Table II). These were the data analysed by the Laboratory of Environmental Studies (Debrecen, Hungary), determined by mass spectrometer with a measurement error of <0·2 per mille. Rainwater ^{18}O (Table III) was sampled at three rain-gauge sites located at different altitudes on the southern border of the mountain range. In addition, to obtain the best interpretation of these data, isotopic analyses of rainwater by other authors were used (Araguás, 1991). The content of ^{18}O and deuterium (D) were not weighted by monthly rainfall, as the study of the variability of the isotopic composition of precipitation was based on a single sampling (6 April 1990).

Effect of altitude on the isotopic composition of the rainwater

There are certain characteristic features in the distribution of rainfall in the region. The entire peninsula receives minimal precipitation during the summer, an effect which is more acute in the southern half. This

Table II. Content in ^{18}O (in ‰) of groundwater samples

Sample code	Oxygen-18	
	June 1993	Sept. 1993
32	–7·80	–
140	–8·62	–
144	–9·02	–9·40
150	–8·40	–
259	–8·35	–
304	–8·47	–8·56
307	–8·23	–
314	–8·67	–8·73
321	–8·60	–
362	–8·16	–
372	–8·37	–8·63
567	–8·23	–
571	–8·65	–
683	–9·25	–9·45
684	–	–9·43
748	–7·35	–
891	–8·01	–
950	–7·84	–
1032	–8·73	–8·63
1054	–8·83	–
1137	–	–8·95

Table III. Content in ^{18}O, deuterium excess d (in‰) of rainwater samples. Data for samples 1 to 10 from Araguás (1991)

Sample code	Altitude (m)	^{18}O	D	d
1	910	–8·23	–45·4	20·4
2	1065	–6·29	–30·6	19·7
3	1540	–7·15	–40·4	16·8
4	1845	–11·30	–72·7	17·7
5	1260	–6·64	–36·6	16·5
6	550	–0·68	7·9	13·3
7	1790	–9·34	–57·0	17·7
8	2030	–8·61	–51·6	17·3
9	1950	–10·90	–72·4	14·8
10	30	–4·25	–22·7	11·3
11	1438	–8·16	–	–
12	710	–6·70	–	–
13	610	–6·05	–	–

phenomenon is related to global atmospheric circulation as, during the summer months, there is a weakening of low-pressure systems entering from the North Atlantic; the Azores Anticyclone, associated with fine weather, is usually the predominant climatic feature. Within the study region, maximum rainfall occurs during the winter when conditions exist that permit the precipitation of the great surplus of water vapour generated over the Mediterranean (Martín Rosales, 1996).

The meteorological situation during rainfall sampling in April 1990 was of a low-pressure system to the north of the British Isles and another over southeastern Spain that was moving slowly eastwards. A depletion of the heavy isotopes (Figure 3) can be identified in the air masses during their ascent and passage over the mountains (Stations 10 to 4). The significant difference in altitude among the stations was the criterion for selecting them. The rain from the stations at lower elevations (10 and 6) is more enriched in heavy isotopes than at the mountain stations. Nevertheless, the richest point (6) is associated with an inland ground site. This fact could be due to a cloud front circulating predominantly from the west. The air masses which provide the precipitation, confronted with the Sierra de Gador, are channelled through the Alpujarran Corridor, discharging first on the northern edge of the mountains.

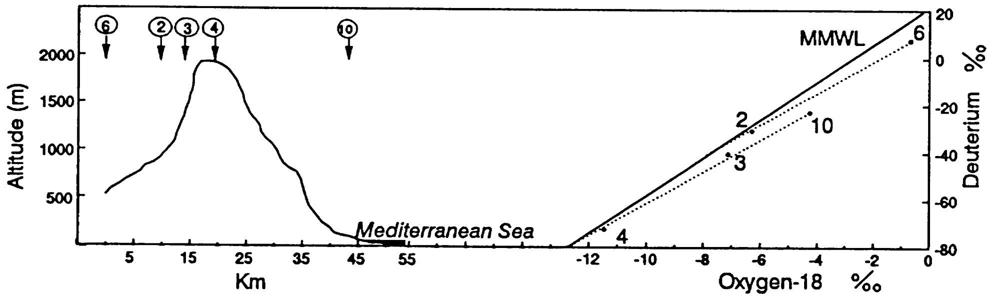

Figure 3. Evolution of the isotopic composition of precipitation samples along the geographic cross-section I–I' shown in Figure 2. The circled numbers correspond to station codes of Figure 2. MMWL is the Mediterranean Meteoric Water Line

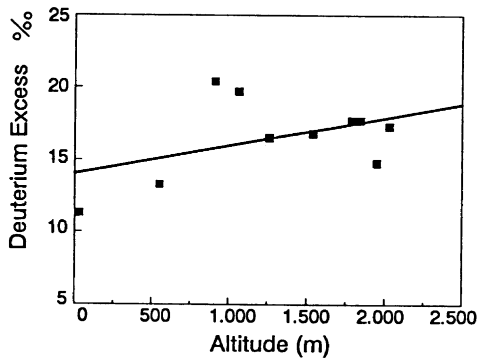

Figure 4. Deuterium excess values of precipitation samples plotted according to altitude of the sampling site

There is a correlation between the *d* values (deuterium excess, defined as $d = \delta D - 8\delta^{18}O$) and altitude (correlation coefficient $r = 0{\cdot}46$). There is a tendency towards higher *d* values at higher altitudes (Figure 4). This effect is known as 'pseudo-altitude' (Fritz *et al*., 1987; Rindsberger *et al*., 1990).

The mean isotopic gradient with altitude can be determined directly from the samples collected at a series of sites located at different altitudes, as well as from a series of rainwater samples obtained by Araguás (1991) on both the northern and the southern slopes of the Sierra de Gador (Table III). The altitude effect has been used to estimate the mean elevation of recharge of waters sampled on the southern slopes of the mountains. The magnitude of this effect on the isotopic composition of the precipitation depends on the climate and the local topography. The $\delta^{18}O$–altitude relationship is shown in Figures 5 and 6. The straight line gradient is –0·32 per mille 100 m for the southern slopes (standard error $S_{er} = 8{\cdot}58 \times 10^{-4}$) and –0·36 per mille 100 m for the northern ones ($S_{er} = 1{\cdot}20 \times 10^{-3}$). These variations are interpreted as the result of the pluviometric differences between the two slopes. The pluviometric gradient is an estimated 26 mm/100 m on the southern slope and 31 mm/100 m on the northern one (Martín Rosales, 1996). When the Sierra de Gador is considered as a whole (Figure 6), the $\delta^{18}O$–altitude relationship obtained is –0·34 per mille 100 m ($S_{er} = 8{\cdot}25 \times 10^{-4}$). The isotope gradients, as a function of altitude, change seasonally and a correction should be considered for the distribution of the altitude within the recharge area (Holdsworth *et al*., 1991). However, as monthly isotopic data for rainfall are not available, these seasonal changes cannot be evaluated for the $\delta^{18}O$–altitude relation.

When the δD values are compared to $\delta^{18}O$ for the rainwater (Figure 7), the samples fall to the left of the Global Meteoric Water Line ($\delta D = 8\delta^{18}O + 10$). This is explained by the contribution to local rainfall that derives from weather fronts coming from the Mediterranean Sea. The broken line in Figure 7 represents the Mediterranean Meteoric Water Line ($\delta D = 8\delta^{18}O + 22$ (Gat and Carmi, 1970)). It can be seen that precipitation of Mediterranean origin must contribute substantially to the recharge of the regional aquifers. Rainfall from fronts which are generated in the Mediterranean has less negative δ values than that from the Atlantic, owing to its shorter track; the shorter distance from the zone where the vapour is generated implies less isotopic

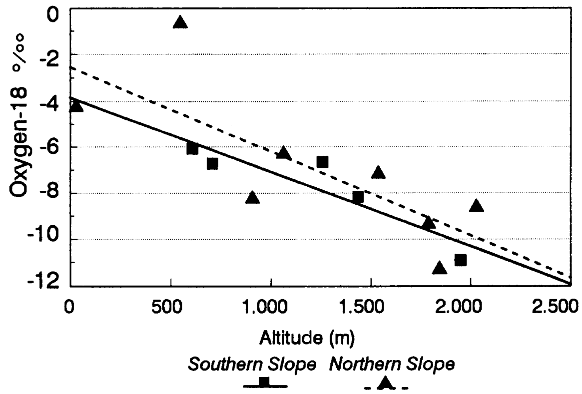

Figure 5. $\delta^{18}O$ of precipitation samples versus altitude of sampling sites up the northern and southern slopes

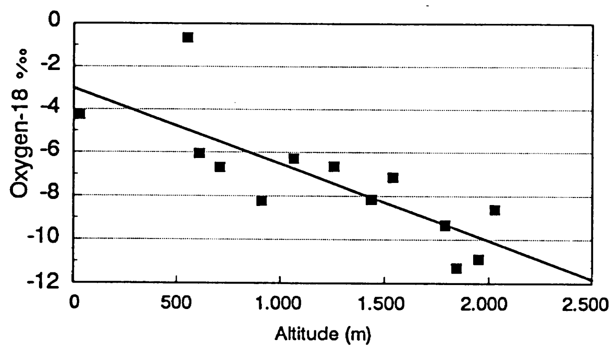

Figure 6. $\delta^{18}O$ versus altitude for all precipitation samples for the Sierra de Gador, undifferentiated

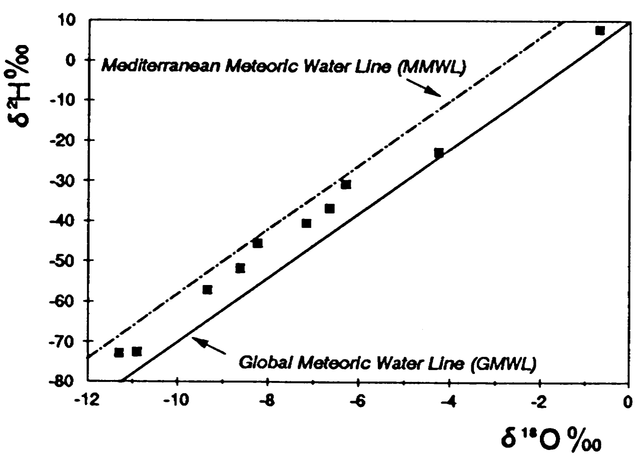

Figure 7. $\delta D/\delta^{18}O$ relationship for precipitation samples from the Sierra de Gador

impoverishment of the water. When the relative contribution of these Mediterranean fronts diminishes, the δ values become more negative. Another factor which may contribute to the precipitation having more negative δ values is the lower mean environmental temperatures prevailing during the winter period.

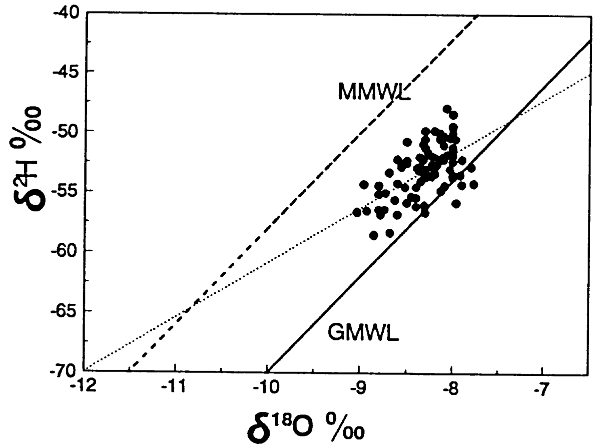

Figure 8. δD/δ^{18}O relationship for well samples from the Sierra de Gador for the period October 1991–March 1993. GMWL is the Global Meteoric Water Line, and MMWL is the Mediterranean Meteoric Water Line

Isotopic composition of the groundwater

The plot of δD values versus δ^{18}O for monthly groundwater samples from the southern Sierra de Gador between October 1991 and March 1993 is shown in Figure 8. It has a distribution following a trend (dotted line) which tends to converge with the Mediterranean Meteoric Water Line (broken line) close to δD = 65 per mille, suggesting the meteoric origin of the groundwater of the area. The dotted line has a slope of 4·5 and is calculated from a linear regression on all data ($r = 0{\cdot}6$). The deviation of data points from the meteoric lines can be attributed to evaporation both during the falling of the rain and by the ground surface before infiltration, i.e. the dotted line defines an evaporation trend. The mean values of deuterium excess in the wells sampled suggest that the precipitation in the groundwater comes from the Mediterranean sector.

The monthly sampling that was carried out for a year and a half, including both rainy months and the dry period, shows δ values that fluctuate between −7·77 and −9·03 per mille and between −47·9 and −58·5 per mille for ^{18}O and D, respectively. The possible existence of seasonal variations in the isotopic composition of groundwater would be more easily demonstrated by examining the equivalent variations in the isotopic composition of rainfall. However, these data are not available due to seasonal absence of rainfall. The samples analysed by other authors for the Sierra de Gador and Campo de Dalias (López Vera and de Miguel, 1983; Domínguez and Custodio, 1994) fall within the same range of δ^{18}O values (between −10 and −7 per mille), again supporting the idea that the principal recharge of the aquifer of Campo de Dalias occurs laterally through the aquifer system of the Sierra de Gador.

Figure 9 displays the monthly variations in ^{18}O content and conductivity, from October 1991 to March 1993, in five wells located at the foot of the mountains, plus the mean monthly precipitation for the southern Sierra de Gador. Conductivity (μS cm^{-1}) is represented on the left *y* axis; δ^{18}O (per mille) is shown on the upper part of the right *y* axis and precipitation (mm) in the lower part. There is a reduction in amplitude of the variations observed in the course of the year as a consequence of the mixing with the volume of water stored in the aquifer. The water reaching the piezometric surface does not clearly reflect the seasonal variations in rainfall as the ^{18}O and D concentrations remain almost constant throughout the year and over successive years. This suggests that groundwater residence time in the aquifers is several years. The isotopic contents of the groundwater are different from those of the rainfall. This also signifies the mixing of infiltration waters in the aquifer. Slight variations in the conductivity and isotopic composition of groundwater show that, in certain cases, there is no homogenization of this mixture, but instead betray faint traces of recent recharge.

The recharge of the groundwater can be regarded as a selection or preferential infiltration of rainwater, with some additional reduction in the variability of the isotopic composition being imposed during descent through the unsaturated zone (Gat, 1971). This selection can tend towards cold-season rains, when evapotranspiration is

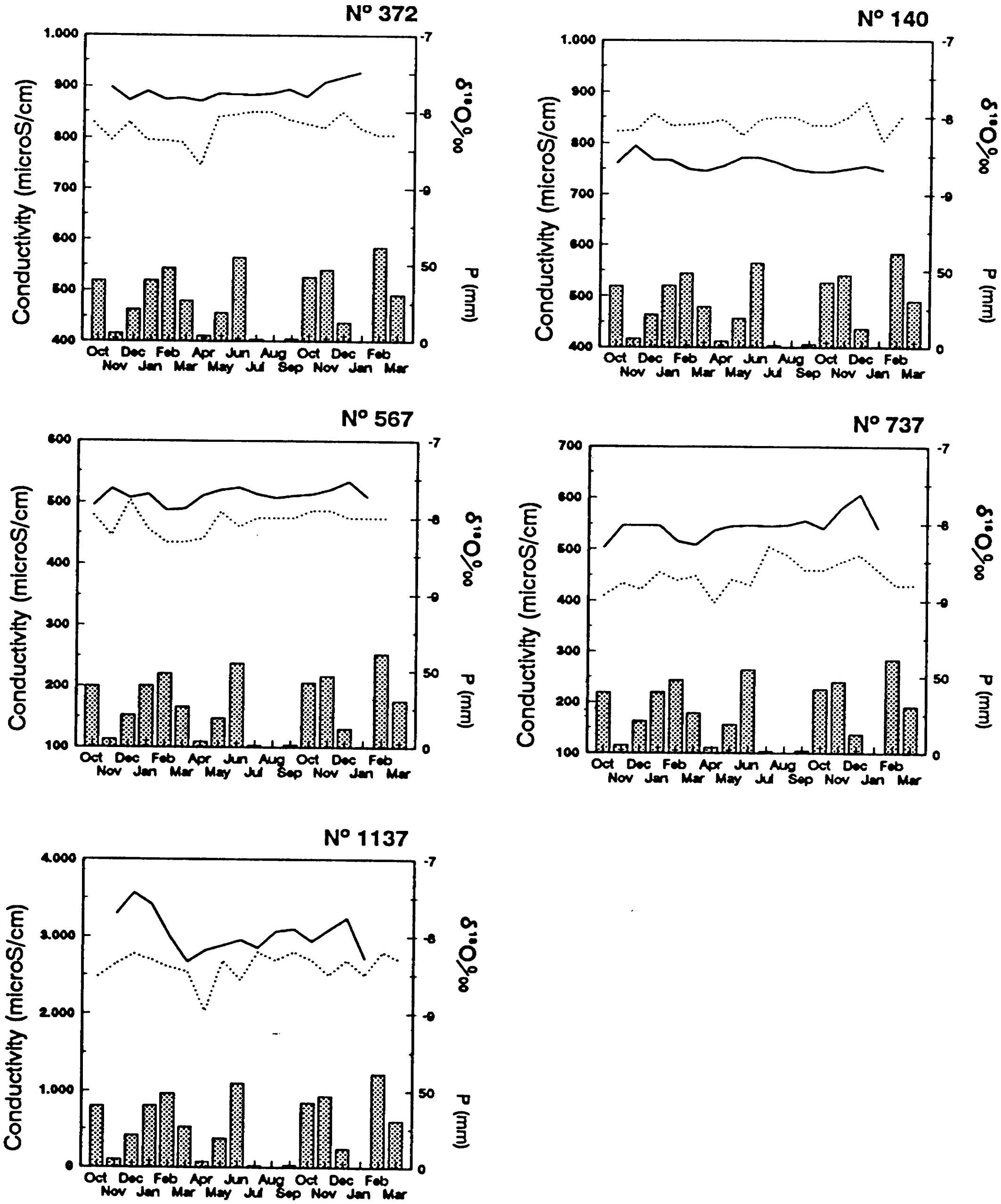

Figure 9. Monthly variation of the ^{18}O content (dotted line) and conductivity (solid line) of the groundwater. The bars correspond to the mean monthly precipitation during the same period

less pronounced and there is enrichment in heavy isotopes, or towards rains of short duration and low intensity (warm season) which result in the infiltration of a greater proportion of the isotopically heavy rainwater in a given air mass.

Figure 10 shows examples of ^{18}O along the contact area between the carbonate massif and plio-Quaternary materials of Campo de Dalias. The data are for June and September 1993. The concentrations range between –7·35 and –9·45 per mille. An isotopic depletion is detected in all the wells analysed on the second occasion, following a hot and dry summer. The waters from wells 144, 683 and 684, with noticeably lighter isotopic contents (reaching –9·45 per mille in ^{18}O in some cases), indicate the presence of a recharge area with fast flow

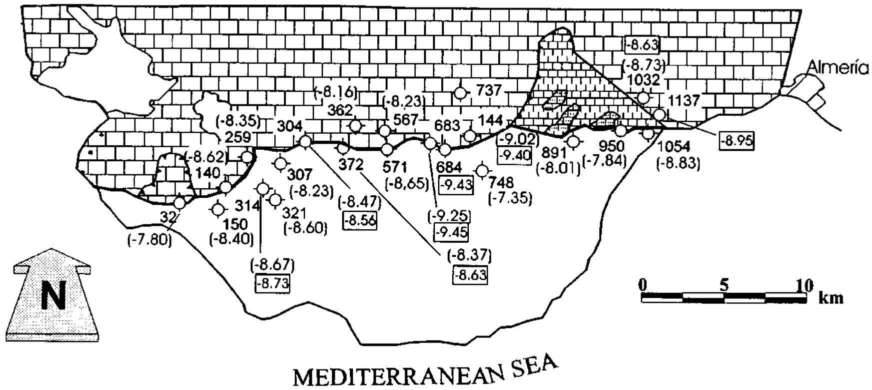

Figure 10. Distribution of the ^{18}O content of groundwater samples. Sample code numbers are in bold. Data corresponding to June 1993 are in parentheses and to September 1993 in a rectangle

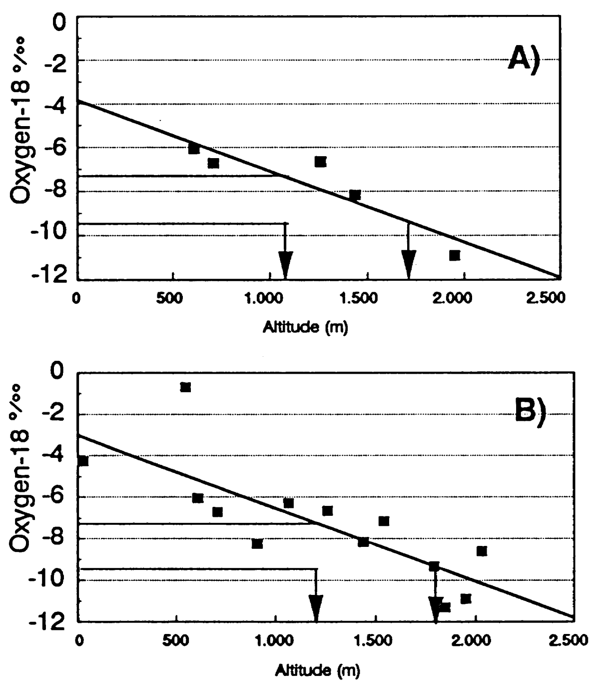

Figure 11. The principal recharge area, based on the isotopic composition of groundwater: (A) southern edge; (B) Sierra de Gador as a whole

and located at a high altitude. Chemical analysis of the water at these points reveals low mineralization; the total dissolved solids concentrations ranged from 330 to 400 mg l^{-1}. Dating based on their tritium content (7·7 and 5·4 TU in wells 144 and 683 respectively) suggests that these samples are younger than the rest, most of which have a tritium content of less than 1 TU. Wells 144, 683 and 684 are situated in the lower sections of gullies, with extensive outcrops of semipermeable materials (calcoschists) and impervious materials (phyllites) higher up the thalwegs. Such basins are prone to strong surface runoff with downstream groundwater recharge, explaining the isotopic compositions. Well 748 displays an ^{18}O concentration of −7·35 per mille, coinciding with the presence of a drawdown cone in the piezometric level around it, with elevations descending to less than 15 m below sea level.

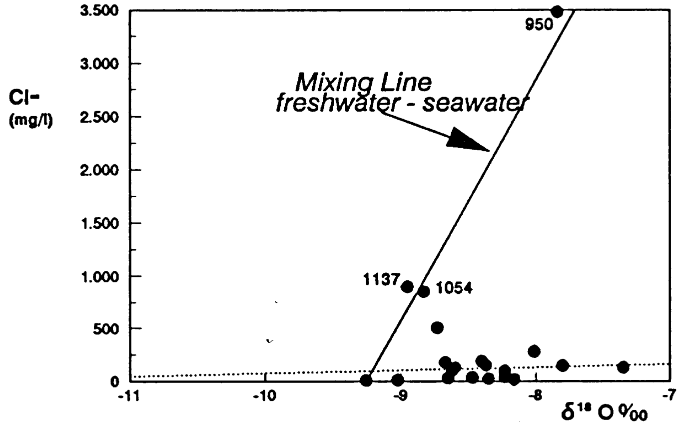

Figure 12. Chloride versus $\delta^{18}O$ of groundwater samples

Based on the linear relationship obtained from the $\delta^{18}O$–altitude correlation in precipitation data for the southern Sierra de Gador (Figure 11), and considering the groundwater isotopic composition, the principal recharge area appears to be located within the zone between 1100 and 1700 m in altitude, possibly in strips where the outcropping rocks are either karstified or denuded of soil, permitting faster infiltration. This area coincides to a great extent with that indicated by the linear relationship for the entire mountain range between 1200 and 1800 m.

Identification of mixing with seawater

The conservative properties of D and ^{18}O in the water molecule, in combination with detection of other ions such as chloride, can identify the primary cause of salinization and eliminate other possible causes.

Figure 12 plots the relationship between chloride content and ^{18}O of the water in the wells that were sampled. Where seawater intrusion is the cause of salinity, the groundwater samples will fall on the mixing line between the compositions of marine and freshwater. This is the case with samples from wells 950, 1054 and 1137 (Figure 12), located in the easternmost sector of the Sierra de Gador where salinity is most serious because of the proximity to the sea. When salinization results from the leaching of salts coming from evaporitic deposits of marine origin, or from the weathering of other superficial rocks and soils, no changes appear in the stable isotopic composition of the infiltrating water. Therefore, there is no relation between ^{18}O and chloride, as can be seen in Figure 11 for the remainder of the sampled wells.

Variations in environmental isotopes contribute to the identification and study of the origin of the salinization of groundwater. Nevertheless, other criteria have also been used, such as the potentiometric charge below sea-level in the easternmost sector and detection of the sodium chloride hydrogeochemical type where high conductivity values (more than 10 000 $\mu S\ cm^{-1}$) coincide with potentiometric highs.

CONCLUSIONS

The precipitation that recharges the aquifers of the region is predominantly of Mediterranean origin. The ^{18}O and D concentrations of the groundwater being extracted remained almost constant over the year and over successive years, suggesting a residence time of several years in the aquifers. There is a mixing of the infiltration waters in the aquifer, leaving traces of recent recharge in some cases.

From the isotopic composition of waters, the construction of new infiltration dams in the mountains would be most advisable within the zone between 1200 and 1800 m in altitude, where the outcrops, karstified or denuded of soil, permit rapid infiltration. In the central-eastern sector of the southern slopes, the circulation of the groundwater flow is faster, coinciding with basins susceptible to torrential runoff.

Environmental isotopes contribute to the determination of salinization mechanisms, which may also be identified by chemical tracers or even, in the simplest case, by measurement of conductivities. The salinity detected in the groundwater must be due to seawater intrusion in the eastern sector of the Sierra; in the remainder of the area the salinity is a result of dissolution of precipitate rocks by the infiltration water.

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